INCREASED CARBON SINK IN TEMPERATE AND BOREAL FORESTS

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Abstract. An intense search is under way to identify the 'missing sink' in the world carbon budget of perhaps 2 Pg year^{-1} (petagrams, or billion tonnes) of carbon, but its location and mechanism have proved elusive. Here we use a new forest inventory data set to estimate the carbon sink and the carbon pool of woody biomass in 55 countries that account for nearly all temperate or boreal forests and approximately half the world's total forest area. In each country there was a net accumulation of biomass; together, the carbon sink of woody biomass was 0.88 Pg year^{-1} during the 1990s with estimated uncertainty from 0.71 to 1.1 Pg year^{-1}. This estimate, already about half of the missing sink, would probably be even larger if carbon accumulation in soil and detritus were also accounted for, but we are unable to quantify that additional sink. The sink is twice that estimated for the woody biomass of these forests a decade ago due to higher estimates for tree growth throughout the region and decreased timber harvests in Russia. In contrast, the new data indicate a carbon pool that is smaller than earlier estimates because of improved data for Russia and Australia.

1. Introduction

Carbon dioxide emissions from fossil fuel combustion and deforestation add about 8 Pg carbon to the atmosphere each year, but the atmospheric carbon pool increases by only about 3 Pg year^{-1} (Prentice et al., 2001). The residual carbon accumulates in oceans and terrestrial ecosystems. Earlier forest measurements have quantified the carbon sink of temperate and boreal forests including trees, soil and detritus at about 0.7 Pg year^{-1} (Sedjo, 1992; Dixon et al., 1994; Goodale et al., 2002). Studies based on atmospheric analyses, however, indicate that the sink in temperate and boreal regions is larger, 1 to 3 Pg year^{-1} (Tans et al., 1990; Keeling et al., 1996; Prentice et al., 2001). The most recent studies suggest that most of this sink, 1 to 2 Pg year^{-1}, is in terrestrial ecosystems but have not been able to robustly identify

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the location nor the mechanism of the sink (Fan et al., 1998; Bousquet et al., 1999; Rayner et al., 1999; Prentice et al., 2001).

We used the latest international forest inventory data set for temperate and boreal forests (UN-ECE/FAO, 2000) to revisit and locate the sink and the pool of carbon in the woody biomass of these forests. Carbon sink refers to the rate of increase in the mass of carbon in the system.

2. Materials and Methods

The forest inventory data are reported by 55 countries for the period of the early and mid 1990s (UN-ECE/FAO, 2000). They cover 2477 million hectares (Mha) of forest and other wooded land (Table I), about half of the world total. They include essentially all temperate and boreal forests, with only Chinese, Korean and South American temperate and boreal forests excluded. The data set is based on a compilation of data from national forest inventories, which rely on field measurements according to well-defined sampling procedures with multiple checking processes, and in most cases continuity of methods over decades (Lowe et al., 1994, 1996; Powell et al., 1994; EC, 1997; Pisarenko et al., 2000). The national data have been adjusted by experts from each country to fit the definitions of the Food and Agriculture Organization (FAO) so that results are comparable across countries. Details of these adjustments are described by country (UN-ECE/FAO, 2000, pp. 71–92, 201–226). Although subject to errors in both the national forest inventories and the adjustment process, these data based on *in situ* measurements taken from hundreds of thousands of statistically representative sample plots are crucial to accurate carbon estimates, since other methods such as remote sensing, eddy-covariance and atmospheric trace gas analyses are still incapable of making these measurements at national or continental scale.

To calculate the carbon sink of woody biomass, we subtracted annual fellings less salvage loggings (annual fellings of natural losses) from net annual increment (Table I) (UN-ECE/FAO, 2000, pp. 155–171). The figures, initially reported by countries as stemwood volumes, were converted to woody biomass by applying country-specific conversion coefficients. These coefficients were calculated from the inventory data separately for the above and below ground biomass of coniferous and decidous trees by dividing biomass by stemwood volume. For the carbon pool, 45 countries reported complete biomass data; missing biomass figures for the other 10 were calculated from stemwood volume using the average conversion coefficients of the reporting countries. Having calculated biomass, we converted it to carbon by multiplying by 0.5, a standard factor for converting woody biomass to carbon (Hakkila, 1989).

Uncertainty in the sink and pool estimates was assessed using uncertainties countries reported for variables that comprised their inventories (UN-ECE/FAO, 2000, pp. 37–39). These reported uncertainties incorporate errors due to mea-

Table I
Definitions of forest inventory terms (UN/ECE-FAO, 2000)

Term	Definition
Forest	Land with tree crown cover (or equivalent stocking level) of more than 10% and area of more than 0.5 ha. The trees should be able to reach a minimum height of 5 m at maturity in situ. May consist *either* of closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground; *or* of open forest formations with a continuous vegetation cover in which tree crown cover exceeds 10%. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10% or tree height of 5 m are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest.
Other wooded land	Land either with a tree crown cover (or equivalent stocking level) of 5–10% of trees able to reach a height of 5 m at maturity *in situ*; or a crown cover (or equivalent stocking level) of more than 10% of trees not able to reach a height of 5 m at maturity *in situ* (e.g., dwarf or stunted trees) and shrub or bush cover.
Standing volume	Volume of standing trees, living or dead, above-stump measured overbark to top (0 cm). Includes all trees with diameter over 0 cm (d.b.h.)
Woody biomass	The mass of the woody parts (wood, bark, branches, twigs, stumps and roots) of trees, alive and dead, shrubs and bushes, measured to a minimum diameter of 0 mm (d.b.h.).
Gross annual increment	The average annual volume of increment over the reference period of all trees, measured to a minimum diameter breast height (d.b.h.) of 0 centimetres (cm).
Net annual increment	Average annual volume over the given reference period of gross increment less that of natural losses on all trees to a minimum diameter of 0 cm (d.b.h.).
Annual fellings	Average annual standing volume of all trees, living or dead, measured overbark to a minimum diameter of 0 cm (d.b.h.) that are felled during the given reference period, including the volume of trees or parts of trees that are not removed from the forest, other wooded land or other felling site.
Natural losses	Average annual losses to the growing stock during the given reference period, measured to a minimum diameter of 0 cm (d.b.h.), due to mortality from causes other than cutting by man, e.g. natural mortality, diseases, insect attacks, fire, windthrow or other physical damage.

surement and sampling in the national forest inventories and those due to the adjustment of the national inventory data to the FAO definitions. A total of 25 countries reported the uncertainty for their estimate of net annual increment, 21 for their estimate of annual fellings and 21 for their estimate of biomass. Since the uncertainty estimates were missing for many countries, we used the largest reported uncertainties for all countries in our effort to indicate the overall uncertainty range. For net annual increment and annual fellings the largest reported uncertainties were 6 and 12%, respectively. We calculated the minimum sink estimate by decreasing the increment and increasing the fellings by these proportions; the maximum sink estimate was calculated by the reverse procedure. The largest uncertainties for biomass and thus for the carbon pool were –9 and +32%.

3. Results and Discussion

3.1. CARBON SINK

In each country, net annual increment exceeded annual fellings, and the growing stock of trees increased. In the whole group of 55 countries, net annual increment totaled 3770 Mm^3, annual fellings 1570 Mm^3 and annual salvage loggings 70 Mm^3. The growing stock thus increased by 2270 Mm^3 $year^{-1}$.

This rate of growing stock accumulation is faster than in inventories taken a decade earlier (UN-ECE/FAO, 1985, 1992) (Figure 1). For simplicity, we term the decade earlier inventories '1980s' although some countries took their inventories in the late 1970s. The figures of the successive inventories must be compared cautiously, because FAO changed the definition of forest and other wooded land between the data sets. In the U.S.S.R., North America and Europe, the forested area was 1890 Mha in the 1980s and essentially the same, 1870 Mha, in this region in the 1990s. However, the difference between net annual increment and annual fellings was 1100 Mm^3 in the 1980s but twice as large, 2060 Mm^3, in the 1990s. In this region, which represents 75% of the forests we analyze, the forested area did not change but the forest biomass is expanding much more rapidly than a decade earlier.

For Europe and North America, the estimate of annual fellings increased from 1180 to 1350 Mm^3 but that of net annual increment increased even more, from 1870 to 2260 Mm^3. Foresters are harvesting more trees, but the trees are growing even faster than chainsaws are cutting. For countries in the Commonwealth of Independent States (CIS), the story is partly different. Estimated net annual increment increased from 1020 to 1320 Mm^3, but annual fellings dropped from 580 to 160 Mm^3 as the forest industry collapsed with the dissolution of Soviet central planning (Shvidenko and Nilsson, 1998).

The figures of net annual increment are higher probably because of both a real increase in tree growth and improved increment estimates. The real increase may

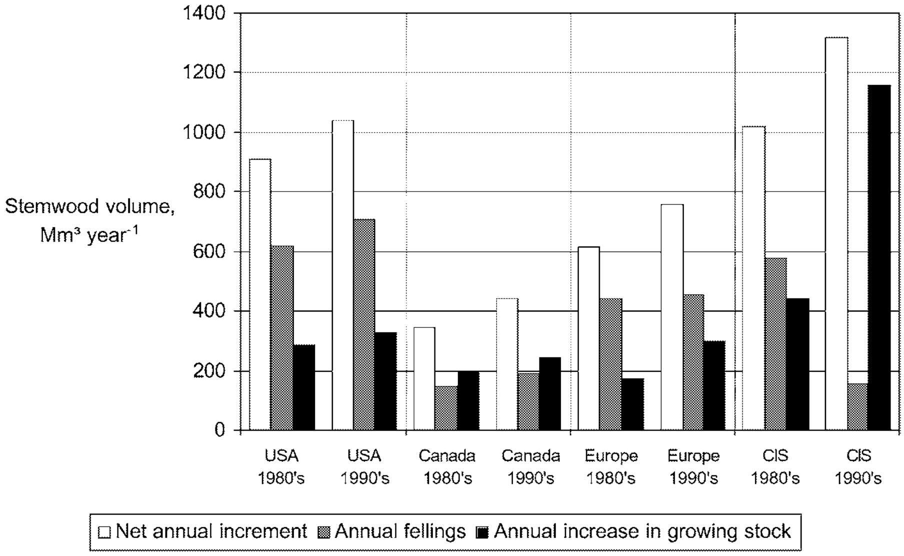

Figure 1. Net annual increment, annual fellings and annual increase in growing stock, the latter calculated as the difference between the former two, of trees in temperate and boreal forests in the 1980s and the 1990s. Inventories termed as '1980s' were taken in some countries in the late 1970s.

be a result of environmental changes, such as rising temperatures and atmospheric CO_2 concentrations (Schimel et al., 2000), nitrogen deposition (Nadelhoffer et al., 1999), and efficient forest management in regions that practice intensive forestry (Kuusela, 1994). In six European countries (Austria, Finland, France, Norway, Sweden, and Switzerland) with large forests and probably the most reliable forest inventories, the net annual increment in the 1990s was 14% higher than in the 1980s. In the other European countries, the increment estimates increased by 16%. The similarity in these figures suggests that, at least in Europe, the higher increment figures are mostly due to a real increase in tree growth (Spiecker et al., 1996).

In terms of carbon, the total net annual increment corresponded to 1.5 Pg year^{-1}, annual fellings to 0.64 Pg year^{-1}, and annual salvage loggings to 0.025 Pg year^{-1}. This results in a carbon sink of 0.88 Pg year^{-1} in the woody biomass for the 55 countries. Uncertainty of the sink estimate ranges from 0.71 to 1.1 Pg year^{-1}. About half of the sink was in CIS countries, mainly Russia (Table II).

Sedjo (1992) estimated that forests in North America, Europe and the U.S.S.R. in the mid 1980s were a sink for carbon of 0.69 Pg year^{-1} with trees accounting for about 0.36 Pg year^{-1} of the sink. This estimate for trees is less than half of our estimate for woody biomass in those same regions in the 1990s (Table II). Dixon et al. (1994) estimated that the total forest carbon sink in North America, Europe, Russia and Australia before the 1990s was 0.57 to 0.95 Pg year^{-1}. They did not report the carbon sink for trees alone, i.e., excluding soil organic matter, detritus and wood products. Recent country-wide analyses on different continents suggest that trees have accounted for 50 to 80% of the total forest carbon sink (Turner

Table II

The sink and the pool of carbon in woody biomass on forest and other wooded land in temperate and boreal forests. Uncertainty in the total sink estimate ranged from 0.71 to 1.1 Pg year^{-1} and that in the total pool estimate from 80 to 116 Pg

Region	Area (Mha)	Carbon sink (Pg year^{-1})	Carbon sink (tn ha^{-1} year^{-1})	Carbon pool (Pg)	Carbon pool (tn ha^{-1})
Europe	215	0.11	0.52	8	39
CIS [a]	934	0.45	0.48	41	44
of which Russia	887	0.43	0.48	40	45
North America	716	0.27	0.38	31	43
of which Canada	418	0.10	0.25	12	29
of which U.S.A.	298	0.17	0.56	19	63
Australia, Japan and New Zealand	613	0.06	0.10	8	13
of which Australia	578	0.04	0.07	5	9
Total	2477	0.88	0.35	88	35

[a] CIS countries are Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, the Republic of Moldova, the Russian Federation, Tajikistan, Turkmenistan, Ukraine and Uzbekistan (UN-ECE/FAO, 2000).

et al., 1995; Shvidenko and Nilsson, 1998a; Perruchoud et al., 1999; Liski et al., 2002). Based on these estimates, the carbon sink of trees in the study by Dixon et al. (1994) may have been 0.29 to 0.76 Pg year^{-1}. The lowest estimate is less than one half of our lowest estimate for the 1990s, and the higher estimate is smaller than our high estimate by one-third.

The present sink estimate for the total of temperate and boreal forests was high because the estimates for the individual regions were either higher than the estimates for the 1980s or at the high end of the earlier uncertainty range. However, the present results contradict recent studies for individual large countries, Russia and Canada.

In Russia, trees on land classified as 'forested area' were reported to have been a source of carbon of 0.04 to 0.06 Pg year^{-1} between 1988 and 1993 (Shvidenko and Nilsson, 1997; Goodale et al., 2002). The results were based on differences in successive growing stock inventories. Unlike the present study, these studies did not account for land classified as 'unforested area'. Such land comprises stands that do not yet, after harvesting or natural disturbance, meet the stocking density requirement of 'forested area' (Shvidenko and Nilsson, 1997). The studies limited to 'forested area' could not account for the regrowth of these recovering stands, and, therefore, may have underestimated the sink. In addition, the estimates could not yet fully reflect the increase in growing stock as a consequence of the decreased fellings (Figure 1), because the fellings decreased mainly after 1993 (Shvidenko and Nilsson, 1998b). Gooddale et al. (2002) explained that the carbon source estimates resulted from improved methods of quantifying the impacts of disturbances. The estimate of natural losses they probably referred to (Nilsson et al., 2000, p. 65) is indeed 70% higher than in the inventory data we used (UN-ECE/FAO 2000, p. 189). But their estimate of gross annual increment is still 100% higher than that, and the residual, net annual increment, equal to the present estimate for forest land only, 970 Mm^3. Despite the higher disturbance estimate, forest balance would remain clearly positive implying increasing tree biomass, and the estimate of the tree carbon sink in Russia would be only 30% smaller.

In Canada, the carbon pool of trees was reported to have decreased during the 1970s and the 1980s after having increased continuously since the 1920s (Kurz and Apps, 1999; Goodale et al., 2002). The decrease was caused by fire and insect disturbances, which were estimated to have increased so much that the associated carbon releases from trees had become larger than carbon uptake in tree growth. In forest inventory terminology, this implies natural losses larger than gross annual increment and, consequently, negative values for net annual increment. In the new inventory data used in the present study, net annual increment was positive however and larger than annual fellings, leading to a considerable carbon sink estimate for woody biomass in Canada. Yet, disturbance areas in the forest inventory data for the 1990s (UN-ECE/FAO, 2000, p. 319) were as large as those in the Canadian study for the 1970s and the 1980s. The present high estimate of net annual increment is also supported by growing stock estimates for Canada. They were larger in the new inventory data than in the data a decade ago (UN-ECE/FAO, 1992). In the Canadian study, the growth rates of age classes of trees were calculated from biomass inventory around 1970, and the growth rates were assumed to be unchanged in time. The new inventory data indicate increased growth rates. A recent remote sensing study detected decreased forest biomass across northern Canada between the 1980s and the 1990s coinciding with the increased disturbance records (Myneni et al., 2001). However, biomass had increased elsewhere so that the Canadian forest as a whole was a carbon sink.

According to the present results, about half of the ‘missing sink’ in the world carbon budget is in the woody biomass of temperate and boreal forests. The total carbon sink in these forests is probably larger, because increased tree biomass can produce more litter and thus induce additional carbon accumulation in soil and detritus (Turner et al., 1995; Shvidenko and Nilsson, 1998a; Perruchoud et al., 1999; Liski et al., 2002). We are, however, unable to quantify this carbon sink from available data. The estimated sink is larger than expected, due to increased tree growth estimates throughout the forested region and decreased harvesting in Russia. Although some atmospheric studies suggest that the sink is largest in terrestrial North America (Fan et al., 1998), the data set we used indicates that the Russian sink is larger than the sink in North America (Table II, Figure 2). The result is broadly consistent with the results from Bousquet et al. (1999), who employed atmospheric measurements and a 3-dimensional atmospheric transport model and

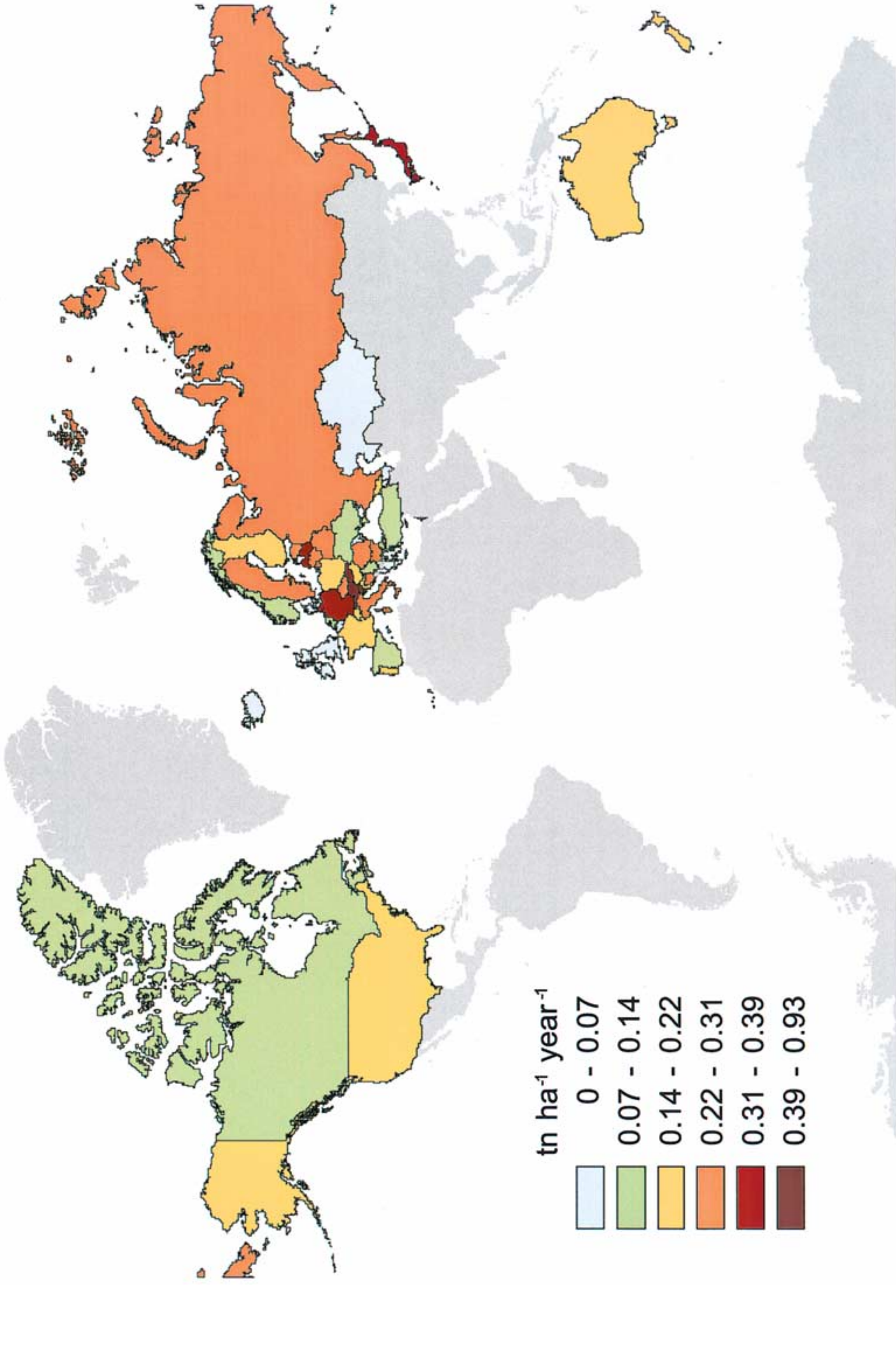

Figure 2. The carbon sink of woody biomass in temperate and boreal forests per unit of total area of the countries.

found a terrestrial carbon sink in north Asia that is three times larger than that in North America. The results are not directly comparable though. The present study includes only trees while the atmospheric studies include additionally forest litter and soil as well as other ecosystems than forests.

3.2. CARBON POOL

The pool of carbon in woody biomass totaled 88 Pg with uncertainty from 80 to 116 Pg. Nearly one half of the pool was in CIS countries, one third in North America, and about 10% both in Europe and in the forests of Australia, Japan and New Zealand (Table II). The pool per unit area of forest and other wooded land was smallest in Australia and Canada, which have open woodlands in the dry and cold margins of forest vegetation, and largest in the U.S.A.

The carbon pool estimates for Europe, Canada and the U.S.A. deviated from earlier ones (Dixon et al., 1994) by only a few percent, whereas for Russia our mean estimate was 46% (34 Pg) smaller and for Australia 72% (13 Pg) smaller. The estimate for Russia is particularly crucial to the accuracy of the overall estimate of the carbon pool of woody biomass in the temperate and boreal forests. In a detailed analysis of Russian forest inventory data and vegetation allometrics, the carbon pool of live and dead forest vegetation was estimated at 31 Pg on 771 Mha forest area resulting on average in 40 tn carbon ha^{-1} (Alexeyev et al., 1995). This is comparable with the estimate of the present study but only about half of the estimate of the earlier global analysis by Dixon et al. (1994). Earlier estimates may have overestimated carbon pools because they were not based on representative samples. Typically, unrepresentative samples tend to bias towards sites with carbon pools larger than average (Botkin and Simpson, 1990).

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